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LEARNING ABOUT HOW AIRCRAFT ENGINES WORK AND FAIL

Irem Y. Tumer *
NASA Ames Research Center
Caelum Research, MS 269-3
Moffett Field, California, 94035
(650) 604 2976
itumer@ptolemy.arc.nasa.gov

Anupa Bajwa
NASA Ames Research Center
Recom Technologies, MS 269-3
Moffett Field, California, 94035
(650) 604 1851
abajwa@mail.arc.nasa.gov

ABSTRACT

This paper presents a series of lecture notes prepared by a group of researchers at the NASA Ames Research Center. The aim of the lecture series is to provide an overview of how aircraft engines work and fail, with the overall purpose of familiarizing the researchers with the general issues. The lectures provide a good introduction to the general topic, and will serve as a starting point for a group of researchers interested in applying their expertise to aircraft engine health monitoring for condition-based maintenance. The paper provides a summary of these lectures, to encourage other researchers to conduct similar reading and lecture series.

INTRODUCTION

A group of researchers at the NASA Ames Research Center has started working on engine health monitoring (EHM). The purpose of the basic research program is to explore ways to use Engine Monitoring Systems to reduce the cost of engine maintenance and to increase safety. The solution the group is aiming for is robust and reliable engine health monitoring and diagnostics systems with improved detection and diagnosis capabilities. The group has a combined expertise in condition monitoring and diagnostics, aeronautical engineering, mechanical engineering, software engineering, and helicopter dynamics and monitoring.

To help with the advance of the engine health monitoring project, the authors have organized a set of engine lectures. The audience is the group of researchers interested in engines. The purpose of the lecture series is to join our expertise in order to understand how aircraft engines work and what failure modes are of concern to the users and designers. In this paper, we summarize the format and content of these lectures, with the purpose of encouraging researchers to conduct similar lecture series in their aircraft engine research. Based on verbal feedback, we know that the lecture series have been very beneficial to all who are involved, and we encourage the readers to use the approach proposed in this paper for their purposes.

Format and Audience

The series of lectures on aircraft engines is designed to help the researchers understand how engines work, and what the various failure mechanisms are that could cause costly damage and potentially result in catastrophic failures. The content of the lectures is directly relevant to the project, which keeps the participants very interested and interactive during the lectures. The lectures are organized once or twice a month to assure that they do not interfere with everyone's work schedules, and to assure that the material is retained between subsequent lectures. A set of suggested readings is proposed by the authors for each lecture, to make sure that the participants will provide valuable insight and feedback during the lectures.

The format of the lectures follows a typical lecture style, conducted on a white board and with transparencies. The lectures are prepared and delivered by the authors of this paper, and complemented by others on a volunteer basis. While it is important to introduce variety to the style of teaching, it is crucial that one or two people are responsible for the entire series of lectures. The tone of the lectures is kept informal and interactive so that the participants provide constructive criticism and feedback. Open discussions are encouraged at the end of each lecture to take advantage of the combined expertise of the researchers involved. In addition, two types of applied lectures are included to enhance the material learned through the lectures: (1) a field trip to a general aviation airport to look at engines first hand, and compare the actual engines to what was learned through the lectures; (2) meetings with pilots to get to ask direct questions about the operation of an aircraft, and the types of problems/failures they have encountered. The combination of interactive lectures with field trips and question-answer sessions by experts provides a great learning environment.

LECTURES AND CONTENT

The lecture series covers a variety of topics, all related to understanding how engines work and how and why they fail. The topics include: (1) an overview of overall engine operation and its main components; (2) an overview of engine performance parameters, such as thrust, and physics laws to analyze engines; (3) a detailed analysis of the compressor and its performance; (4) a detailed analysis of the combustion chamber and its performance; (5) a detailed analysis of the turbine and its performance; (6) a review of basic thermodynamics and fluid flow equations; (7) a review of the different types of engines and their characteristics; (8) a study of maintenance-related defects and failures and their indicators in aircraft engines for condition-based monitoring; (9) a literature review of engine monitoring and diagnostics systems. These lectures were complemented by other related topics such as: (1) failure modes and effects analysis; (2) thermodynamics principles, airbreathing engines and rocket engines; (3) the role of communications among maintenance personnel; (4) overview of machine learning and knowledge discovery techniques; (5) statistical pattern recognition techniques. A summary of some of these topics is provided in the following lectures. Only the topics relating to the understanding of how engines work and fail are included in this paper.

Engine Operation and Main Components

The lecture series starts with a general overview of a typical aircraft engine layout and components, followed by the overall operation of the engine and the interaction of each component [3, 4, 5, 6].

A gas turbine is an internal combustion engine which produces power by the controlled burning of fuel; a machine designed to accelerate a stream of gas, which is used to provide the reactive thrust necessary to propel the aircraft. Thrust is the underlying principle which forms the basis of jet propulsion, and is generated when there is a variation in momentum (mass times velocity, $p = mV$). The jet engine's purpose is to increase the momentum of the airstream passing through it. Thrust is generated in two ways: (1) move a small quantity of air through the engine and accelerate it to a very high speed; even though the mass of the air is small, the increase in velocity is high, so the overall momentum increases; and, (2) accelerate a large amount of air to a somewhat higher velocity than outside air; the change in velocity is small, but the mass of air is large, so the overall momentum increases. The first part, called the primary air (15%), goes through the core of the engine, i.e., the compressor, etc. The second part, the bypassed air, provides "cold" thrust, and keeps the engine cooler, quieter, and more fuel efficient.

A gas turbine has three main components: compressor, combustion chamber, and turbine, as shown in Figure 1 [2]. Air enters through the air inlet at around $450 mph$, and is passed through the compressor. The compressor increases the pressure of the airstream. This is accomplished by supplying mechanical work to the compressor, whose rotating blades and stators for each stage increase air pressure by decreasing velocity (diffusing action). The highly compressed air then is discharged into the combustion chamber, at about $600F$. Inside the combustion chamber, fuel is injected and burned, adding tremendous energy to the airstream, resulting in high pressure and high temperature gas. The hot gas enters the turbine section at around $1600F$. Inside the turbine, the increased energy is absorbed from the gas, converting potential energy into kinetic energy. The turbine is rigidly linked to the compressor and converts the gas energy into mechanical work to drive the compressor and other engine systems (pumps, AC, etc.). The remaining air is ejected at the outlet exhaust at a very high velocity. Thrust contributions from, and pressure distribution along, the various components is shown in Figure 1. Thrust is generated in all parts of the engine, and the resultant thrust vector propels the engine, and hence the aircraft, forward.

Engine Physics Laws

The thrust equation, derived from the theorem of momentum, is the most important equation in jet propulsion theory [2, 3, 7]. Engine thrust, T, is calculated by summing all of the forces acting on the engine and equating this to the timewise variation in momentum. The resulting thrust equation is:

$$-T = \dot{m}(C_9 - C_0) - A_9(P_9 - P_0) \tag{1}$$

where C_9 is the jet exhaust velocity, C_0 is the intake velocity, A_9 is the exhaust area, $\dot{m}$ is the mass flow rate, and P_9 and P_0 are the static pressures at the respective areas.

In addition to the thrust equation, the basic laws in fluid dynamics that are of paramount importance are: (1) conservation of mass, and, (2) conservation of energy. Conservation of mass dictates the same amount of fluid must flow through every cross section, or $\dot{m}_1 = \dot{m}_2$, where $\dot{m}$ is the mass flow rate, equal to ρVA, with ρ being the density, V the velocity, and A the cross-sectional area. This law results in the following relationship, which gives the exhaust velocity:

$$V_2 = \frac{\rho_1 A_1}{\rho_2 A2} V_1 \tag{2}$$

Conservation of energy dictates that the energy contained in the gas when entering the control volume, plus energy added or extracted within the control volume, equals the energy of the gas leaving the control volume. The resulting energy balance gives us the first law of thermodynamics, which provides the necessary temperatures:

$$C_v t_3 + \frac{P_3}{\rho_3} + \frac{C_3^2}{2} + \frac{Q}{\dot{m}} = C_v t_5 + \frac{P_5}{\rho_5} + \frac{C_5^2}{2} \tag{3}$$

where C_v is the specific heat, t_3 is the temperature, and Q is the heat added in the combustion chamber.

Engine Performance Parameters

For aircraft engine designers, several parameters are of interest. *Thrust* is the most important parameter for engine classification, as derived in the previous section [2, 3]. *Specific Fuel Consumption* (SFC) is the second most important parameter to determine engine performance. SFC defines the amount of fuel used to achieve one unit of thrust over a finite period of time. *Specific Thrust* assesses how efficiently the airflow of the engine is converted to a propulsive force. This parameter defines how much thrust is achieved by one unit of mass flow rate, and is used to compare jet engines. *Thrust related to frontal area* characterizes aerodynamic efficiency, relating thrust to the maximum cross-section of the engine. Aerodynamic drag will increase with engine cross section, which implies a need to keep the engine maximum diameter small.

Compressor

The compressor is one of the most crucial components of a gas turbine engine, where the large number of rotating components represents a significant candidate for engine failures [3, 7]. The compressor's operation, performance parameters, and design are discussed, including the mechanics of how air is compressed using the multiple stages of rotors and stators.

The task of the compressor is to increase the pressure of airstream furnished by the air intake. This task is accomplished by supplying mechanical work to the compressor, whose rotating blades exert aerodynamic forces to the airflow. At the compressor outlet, a stream of highly compressed air is discharged to the combustion chamber, where more energy is added in the form of heat.

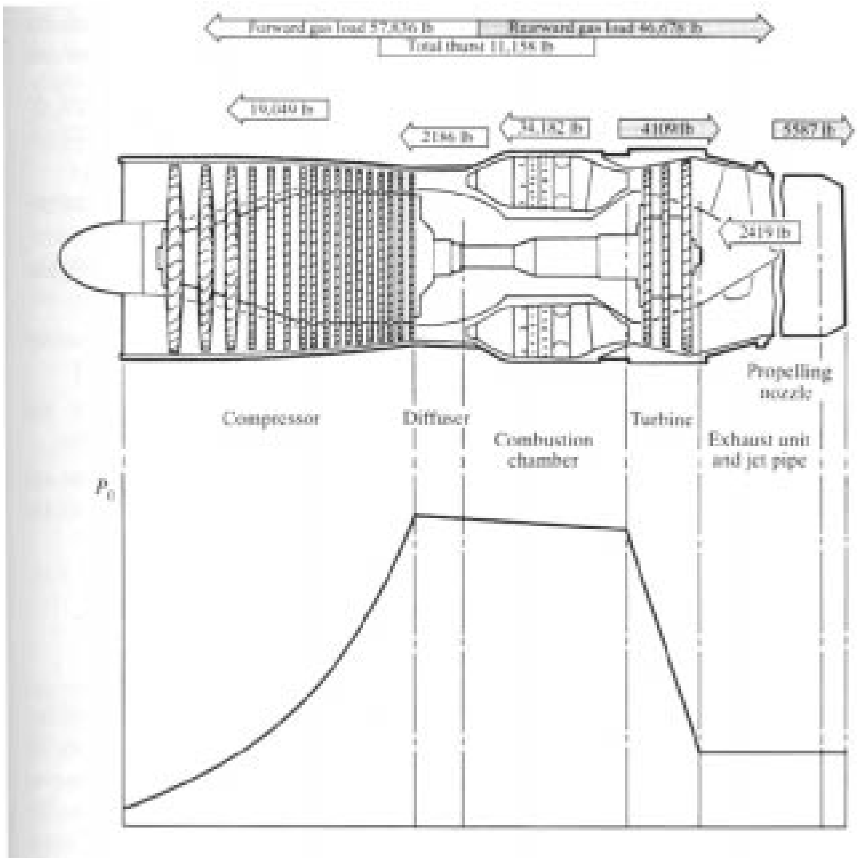

Figure 1. A Gas Turbine Engine

At the compressor stage, mechanical energy is being converted into pressure energy. The amount of energy required and the quality achieved are characterized by several performance parameters. *Compressor efficiency* is the amount of energy supplied to the compressor from the turbine by means of the rotor shaft. *Compressor total pressure ratio* is the ratio of the total pressure at compressor discharge and the total pressure at the compressor entry. This parameters bears directly on thrust, fuel consumption, and engine efficiency. *Air mass flow rate* is the airflow volume that the compressor is capable of processing per second. This parameter allows engine classification with respect to engine size. These three parameters are closely interrelated (e.g., a change in mass flow rate will affect pressure ratio and engine efficiency). For present day compressors, the typical values for these parameters are: 90% efficiency, $16:1$ compression ratio ($30:1$ for high bypass turbofan engines), $200 kg/s$ mass flow rates ($900 kg/s$ for high bypass turbofans).

The majority of engines use axial flow type compressors, due to their ability to handle large mass flow rates, which is a prerequisite for high thrust. The benefits of axial flow compressors (as opposed to centrifugal compressors) are uniform air flow because of the axial direction and reduced aerodynamic drag because of the smaller cross section.

Axial compressors have between 8 and 16 stages of compression. Each stage consists of a rotor wheel carrying rotating blades, followed by a stator assembly carrying stationary vanes to counteract the swirl from the rotor. A compressor stage is shown in Figure 2, where the three dimensional rotor and stator assembly is mapped onto two dimensions to understand the relative and absolute velocities for each stage.

The flow approaching a rotating blade at some ab-

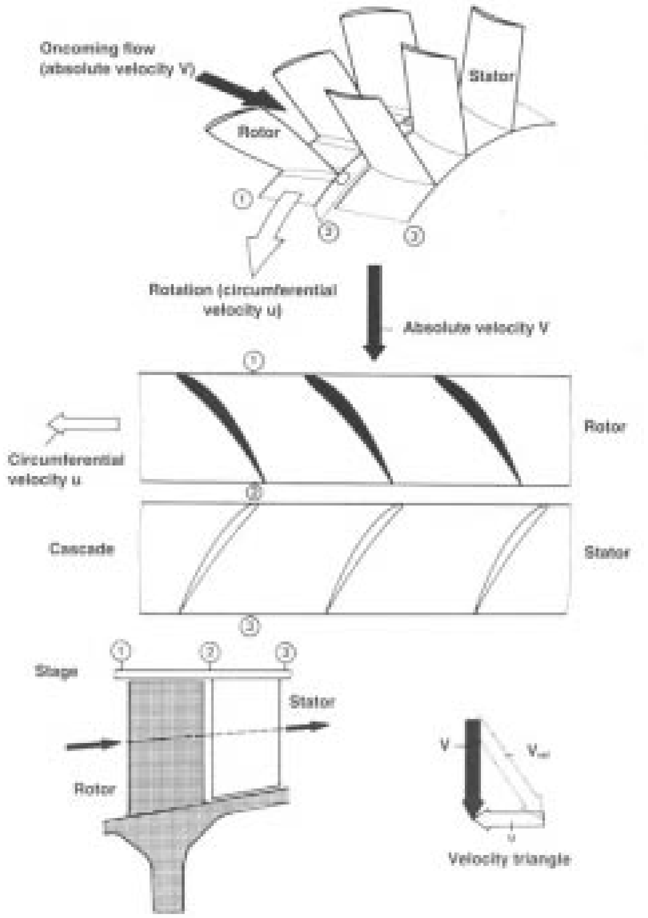

Figure 2. A Compressor Stage

solute velocity V will be viewed by the blade as approaching at some relative velocity V_{rel}, because the blade itself is rotating at a circumferential velocity U. In two dimensions, the absolute velocity is as seen by an external observer sitting next to the engine, whereas the relative velocity is as seen by an observer sitting on the rotating blade and moving with it. All three velocities can be combined into a velocity triangle as shown in Figure 2 [3].

The geometry of the blades is designed such that there is an increase in the cross-sectional area between adjacent rotor blades downstream. This results in a diffusing action causing the relative velocity to decrease and the pressure to increase. The maximum pressure rise possible with a single stage is only $20-30\%$ (1.2-1.3 compression ratio). A typical multistage compressor boosts the pressure by a ratio of 15. After exiting the last stage, the pressurized air is ready for the combustion process.

Combustion Chamber

The second component of importance in a gas turbine engine is the combustion chamber, where the high temperatures can cause serious failures, and where the fuel efficiency represents a direct measure of cost to airline companies [3, 4, 7]. The basic task of the combustion chamber is to provide a stream of hot gas that is able to release its energy to the turbine and nozzle sections of the engine. Following the compression stage, heat is added by the burning of a combustible mixture of vaporized fuel and highly-compressed air.

A schematic of the combustion chamber [3] is shown in Figure 3. Airflow is discharged from the compressor and enters the combustion chamber at a velocity of around $150 m/s$ ($490 ft/s$), which is far too high to sustain a flame. As a result, it is first necessary to slow down the airflow, which is achieved by the forward section of the chamber, formed as a diffuser (the flow passage cross-section is increased in the downstream direction, as shown in Figure 3). The diffuser action decreases the airflow velocity to around $25 m/s$ ($80 ft/s$), which is still too high. The airflow is further reduced by a perforated disk that surrounds the fuel nozzle (drag reduces the flow velocity). When the velocity is reduced to a few meters per second, the airstream enters the flame tube (see Figure 3).

In the flame tube, it is crucial to accomplish the correct fuel/air mixture for efficiency. The fuel/air mass ratio (ratio of fuel mass injected per second to air mass forced each second), ranges between 1 : 45 to 1 : 130. For efficient combustion, the mixture ratio needs to be around 1 : 15. The correct apportioning is accomplished by drag-producing swirl vanes that reduce flow velocity even further. Only 20% of the total mass of the core airflow enters the combustion chamber. The largest part of the flow is ducted around the internal flame tube, where gradual mixing occurs through the holes behind the primary combustion zone.

The parameters that define the combustion chamber characteristics are combustion efficiency and total pressure loss. *Combustion Efficiency* is defined as the ratio of heat released (Q) to the heat theoretically available (Q_0), which is around $90-98\%$. The exact apportioning of fuel and air is difficult to achieve. *Total Pressure Loss* is defined as the ratio of the total pressure at the combustion chamber discharge, to the total pressure at the chamber's entrance, is around $0.93-0.98$, implying a pressure loss of $2-7\%$. The aim is to attain combustion at constant pressure. But some loss happens due to the swirl necessary for efficient combustion and due to friction.

Turbine

The third engine component of importance is the turbine, where fast-rotating blades face extremely high temperatures and, thus, are prime candidates for failures [3, 7]. The turbine's expansion process is explained in detail and contrasted to the compressor's reverse operation.

The primary task of the turbine is to drive the compressor, as well as other systems such as the fuel pump, oil pump, and electric generator. The purpose of the turbine section is to convert the kinetic energy of the combustion chamber exhaust gases into mechanical energy to operate the compressor and the rest of the systems. About $60-80\%$ of the total energy of exhaust gases goes to this purpose. The remaining $20-40\%$ is used to add thrust to propel the engine forward. The turbine power can reach up to $50,000 hp$, and is accomplished by extracting the energy contained in the hot gas. Note that a single turbine blade alone may contribute as much as $250 hp$, which is more than a large car engine can provide.

Basically, the turbine operation is equivalent to that of the compressor, but with the opposite function. The compressor adds energy to the airflow passing through it by converting mechanical energy into pressure energy. The turbine, on the other hand, absorbs energy from the gas flow to convert it into mechanical shaft power. Each turbine stage has two basic elements: a stator and a rotor. The stator is a set of stationary nozzle guide vanes, whereas the rotor is a set of rotating blades, called the turbine wheel. The stationary blades are designed and placed in such a way that there is a narrowing flow path between adjacent blades, which accelerates the hot gas to high velocity, which then turns the rotating part (turbine wheel). Recall that this is the opposite of the compressor, where the blades were causing a nozzle action, rather than a diffusing action. The air flows through this restricted area, where a portion of the heat and pressure energy of the hot gas is converted into kinetic energy, which, in turn, is converted into mechanical energy, when the air hits the rotor blades, which then drives the compressor via the rigidly-linked shaft.

Think of the turbine as having the same function as a water wheel. The gas flow enters the nozzle blades at absolute velocity C_0, and exits at a much higher absolute velocity C. Gas expansion only occurs in the stationary part of the turbine, where potential energy is converted into kinetic energy. The gas exiting from the nozzle at high velocity hits the rotor blades. The consequent action is wheel rotation. The flowpath is kept constant between adjacent rotor blades to make sure that pressure remains constant. Turbine efficiency is defined as the ratio of the actual specific turbine power to the ideal specific turbine power, which is around $0.78-0.92$, due

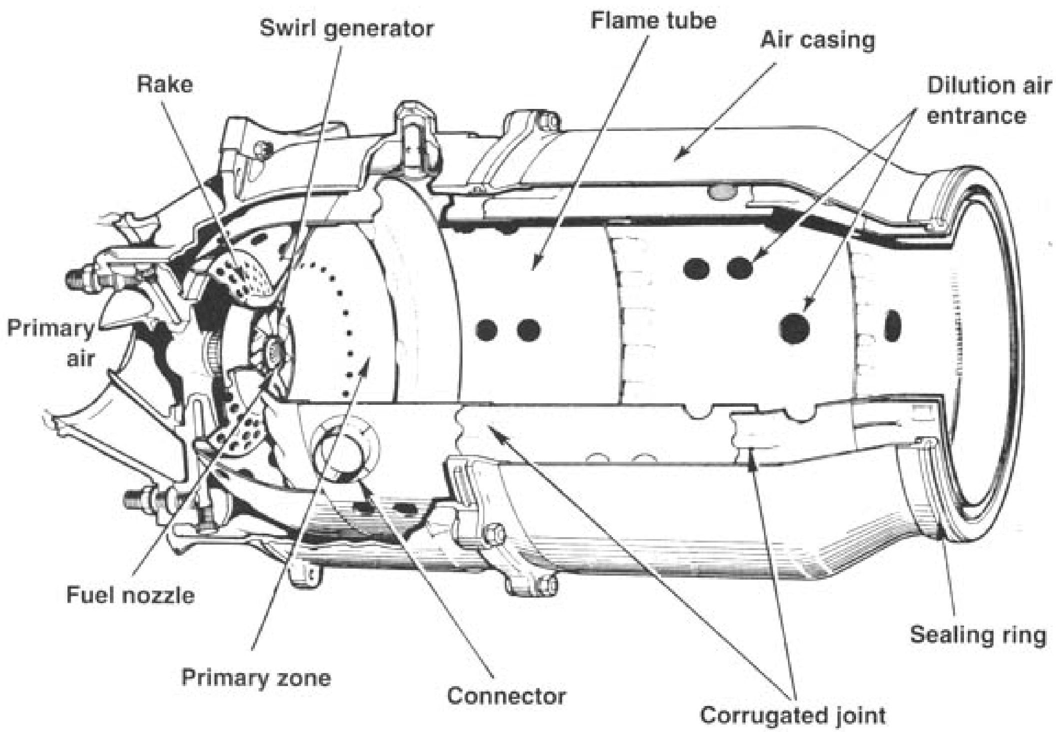

Figure 3. The Combustion Chamber: Typical Burner Assembly.

to losses from the turning of the flow, friction, leakage between rotating and stationary components, and tip clearance.

Gas Turbine Engine Maintenance and Defects

Maintenance of gas turbine engines is done on-wing and while on overhaul. On-wing (or line) maintenance is performed while the engine is installed, to make sure of airworthiness; overhaul or shop maintenance is performed once the engine has been removed from an aircraft, to return an engine to an airworthy condition [1, 7]. On-wing maintenance includes scheduled (for periodic and recurring inspections, based on time limits); and unscheduled (not related to time limits, due to FOD, lightning, heavy landing, etc.) maintenance. Condition-based maintenance is a concept that is gaining acceptance in maintaining gas turbine engines, where devices of increased efficiency and reliability will eliminate a number of the traditionally accepted scheduled checks. The main idea is to overhaul only when they need major maintenance, thus saving in maintenance costs.

The length of time between overhauls (TBO) has increased dramatically. TBO varies considerably between engine types. It is established by the equipment operator and the engine manufacturer, along with the Federal Aviation Administration (FAA). The factors affecting TBO are type of operation and use, servicing facilities, experience of maintenance personnel, total experience gained with a particular engine (TBO may be extended if components inspected for signs of wear and impending failure do well; frequent stops and starts which result in rapid temperature changes will reduce the TBO). Overhaul includes a complete disassembly and inspection by the manufacturer or at approved overhaul stations. Nonrepairable parts are discarded, repairable parts are processed and then given rigid inspection and testing to ensure their serviceability.

Typically, specific guidelines are provided for the types of damage and the extent of the damage for the most critical engine components, to determine whether it should be repaired or replaced. During overhaul, critical components are fan blades (subject to foreign-object damage drawn into the inlet of the engine, such as rocks, which lead to nicks and scratches), compressor blades (same damage as fan blades), turbine nozzles and vanes (first-stage HPT nozzles and vanes receive highest temperatures during operation since they are exposed to the gases that exit from the combustion chamber, which lead to cracks, stress-rupture cracks, burning, etc.), and, turbine blades (centrifugal stresses to which turbine blades are subjected require that the blades be free of cracks in any area, and free of nicks or dents in the root area; no burning or distortion is allowed.)

Inspection of the engine components depends on the type of operation to which engines are subjected (i.e., flight cycle vs. total hours of engine operation). These limits are compared with life limits of parts such as compressor, turbine blades and disks. For example, a commuter airplane between LA and SFO accumulates 12 h of operation and 15 flight cycles. A transpacific flight to Hong Kong accumulates 18 h of operation and 3 flight cycles. Wear, erosion, and heat damage are greater for the commuter engine since there were more engine starts and shutdowns; the commuter airplane engines will have to be inspected and maintained more often. Likely conditions to be found during inspection are burning, chipping, corrosion, cracks, pitting and others. A comprehensive list, gathered from experience of airlines and engine manufacturers, is in [7].

These conditions can be detected using various techniques, including visual, chemical, ultrasonic vibrations, x-rays, magnetic-particle, dye of fluorescent penetrant, borescope, videoscope inspection techniques. Borescope inspection is the most important detection technique used during maintenance, and is necessary for inspecting cracks, stress, corrosion damage, etc. The borescope is used extensively for examining the inside of turbine engines (like a periscope); a tube is inserted through engine borescope ports located in the engine case at critical areas.

Periodic inspections are required after a given number of operation hours, flight cycles, or a combination (dependent upon airline, manufacturer, and maintenance crew), has been exceeded. Time and Cycle limits are logged and compared to life limits (established by manufacturer) of critical parts such as compressors, turbine blades, and disks. Nonroutine inspections are due to events during operation that cause the engine to require immediate special inspection to determine whether the engine has been damaged and what corrective actions must be taken. Some examples are given in the following paragraphs.

Foreign-Object Damage (FOD) This condition is defined as anything from small nicks and scratches to complete disablement or destruction of the engine. The flight crew is often not aware of FOD; however, in case of extensive damage, it will be indicated by vibration and changes in the engine's normal operating parameters. For example, damage to compressors or turbines results in an increase in EGT, decrease in EPR, and a change in the rpm ratio between the core engine and the fan section (N2/N1). The inspections that are required include: external inspection for substantial damage to fan section and inlet guide vanes; borescope inspection of interior of the engine if external damage is not substantial; slight damage to vanes, fan blades, and compressor blades can be repaired if manufacturer limits are not exceeded.

Overlimit Operation for Temperatures This condition is often caused by a malfunction of the engine fuel control or a malfunction in the engine. At starting, EGT is most critical parameter to monitor. If limits are exceeded but not high enough, a borescope inspection is required without overhaul. The hot section of the engine is checked for indications of burning or metal distortion due to excessive heat. If the engine was operated at excessive temperatures, a detailed list of borescope inspections required to inspect for cracks, burned areas in the combustion chamber is provided, including: carbon buildup in the fuel nozzles; first-stage and second-state HPT nozzles for cracks, burned areas, warping, plugged cooling-air passages; HPT rotor for cracks, tears, nicks, dents, metal loss; turbine midframe liner for cracks, nicks, dents, burns, bulges, gouges; first-stage LPT nozzle for cracks, nicks, dents, burns, etc.; LPT stator assembly as above; LPT rotor assembly as above (no cracks allowed in any turbine blades).

Overlimit Operation for Speeds The primary concern for this condition is with rotating assemblies. For overspeed operation at 116-120 % rpm, check fan rotor for rotation, fan shroud for rub, low-pressure compressor with a borescope, inlet and exhaust nozzles for particles, all four stages of the LPT with a borescope for blade and vane damage. If fan speed exceeded 120 %, removal of fan rotor, fan midshaft, and LPT rotor required for inspection. If the core engine (HP compressor and HP turbine) operated between 107-108.5 %, inspect nozzles for particles, core compressor for blade and vane damage, HPT for blade damage.

Other Operational Inspections These are events which happen occasionally that require special attention: fire damage, operation without oil pressure, accident damage, engine stall.

Engine Performance Monitoring

Some of the defects discovered during regular and non-regular maintenance can be detected in advance by monitoring [7] specific combinations of performance parameters during the flight as shown in Figure 4 . Such prior and timely detection of failures saves in maintenance costs. Unfortunately, as of yet, not all defects are yet detectable by performance monitoring.

A recent trend in monitoring the gas turbine engine's day-to-day condition, engine performance monitoring is proving to be very effective in providing early warning information of ongoing or impending failures, thus reducing unscheduled delays and more serious engine failures. The goal is to have these performance parameters as a reliable indicator of developing defects and impending failures that are detected and repaired during inspection and overhaul (presented in the previous section).

The parameters to determine aerodynamic performance include EPR (engine pressure ratio); F/F (fuel flow); RPM (speed); EGT (exhaust gas temperature); throttle position. The parameters to evaluate mechanical performance include vibration amplitude and oil consumption.

Cockpit instrument readings taken ONCE a day, or on every flight during cruise conditions. Recorded data is processed and compared to "normal" data established by the manufacturer or the operator. Data may be collected automatically during flight and then off-loaded for later analysis by ground personnel.

Engine Malfunction Examples Certain kinds of engine failures will result in specific changes in the parameters being monitored. The following, summarized by Pratt & Whitney citetraeger96, are examples of failures detected by engine performance monitoring techniques. The early detection of these failures will save the airlines in maintenance costs. Failures that cannot be detected by monitoring engine parameters can be detected by maintenance inspection techniques, described in the previous section.

Failures due to air leakage from compressor cage A number of compressor section failures, may be due to the failure of bleed air duct external to the engine, a stuck overboard bleed valve, or failure of the engine casing. This failure causes a drop in EPR (engine pressure ratio directly related to the pressure ratio across compressors during cruise conditions, since the turbine expansion ratio is fixed). To regain EPR, throttle is pushed forward, hence increasing fuel flow, which in turn increases inlet temperature, power generated by turbine, and rotor speeds (observe increase in EGT, N2, F/F).

Compressor Contamination Engine performance is decreased due to compressor contamination. Contamination may be due to: operation near salt water; use of impure water for water injection; oil leak in the forward part of the engine that may cause fine dust to adhere to blades. Effects are eliminated by water washing or carbon-blasting of the engine. Contamination of compressor blades changes their aerodynamic shape, roughens their surface, and reduces the airflow area; reduced airflow area reduces compressor efficiency and airflow capacity; when compressors lose efficiency, more power and higher rotational speeds are required to achieve EPR. Additional power is obtained by pushing the throttle forward, increasing fuel flow, and turbine inlet temperature. The throttle motion increases the speed in the low compressor relative to the speed in the high compressor (observe increase in EGT and N2).

Mechanical Failures The loss of parts along the gas path reduces compressor efficiency (unlike contamination, mechanical failures involve only a few blades or vanes). The efficiency loss due to these failures is small, which makes them difficult to detect using monitoring. More severe failures are detected at high power settings when EGT limits are exceeded and/or compressor stalling occurs. Broken blades and vanes result in N1 and N2 increases to overcome efficiency loss, and F/F and EGT increases to provide additional energy. If metal contact is taking place, one rotor system may drop in speed. Parts leaving the compressor may cause for-

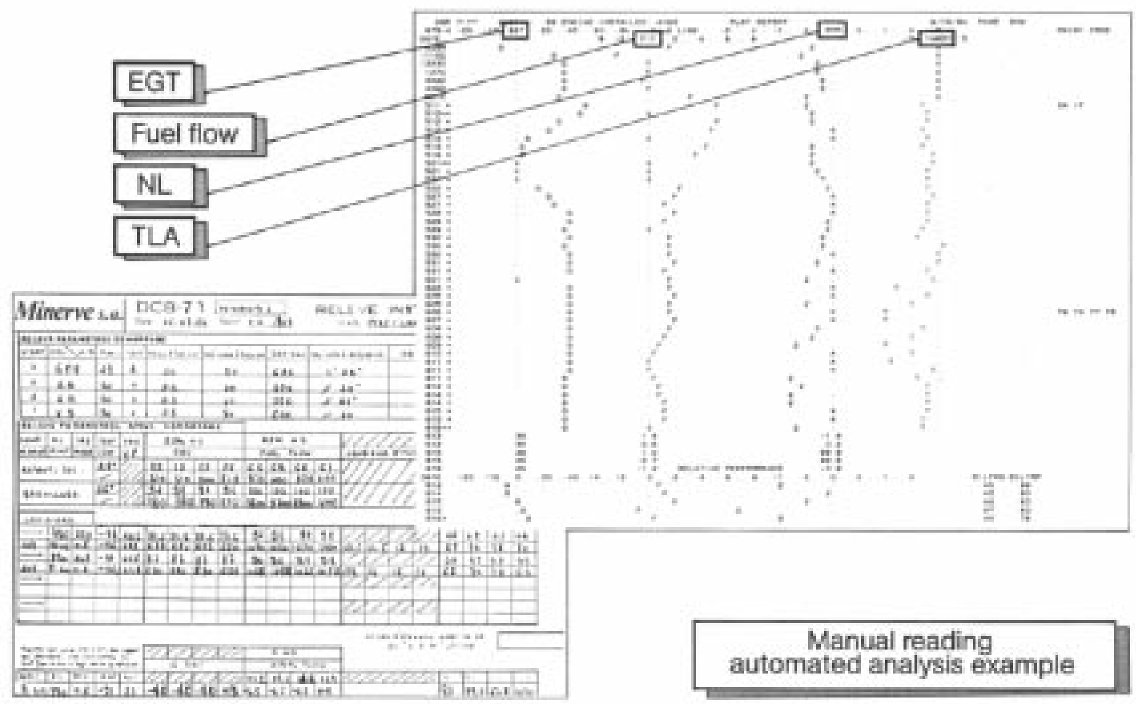

Figure 4. Engine Malfunction Detection by Performance Monitoring.

eign object damage further downstream, and cause a change in performance at the burner section and/or at the turbine section.

Combustion Section The burner section is the least sensitive to failure detection using in-flight monitoring techniques. Failures are due to blocked fuel nozzles, fuel line leaks, failure of a burner itself. These problems must be detected by maintenance monitoring techniques. If the problem becomes severe enough to affect another section of the engine, in-flight monitoring can detect those failures. The most common section affected is the turbine section. In this case, parameters associated with turbine efficiency loss can be monitored, presented next.

Turbine Failures Engine monitoring is very useful in detecting trouble areas in the high-pressure turbines. Loss of a first stage blade causes a marked shift in several performance parameters (whereas blade loss in compressors could go undetected). There are relatively few blades in the turbine to develop the work required to drive the high pressure compressor; hence, a slight loss in turbine efficiency will be very noticeable in engine performance. It is difficult to determine the exact parameter shifts, but, a general pattern appears in cases involving the high pressure turbine. Loss of turbine efficiency (broken blade or seal erosion) or an effective increase in turbine inlet area (bowed nozzle guide vanes), cause the turbine to absorb less than the desired work, which results in a drop in N2. For a given EPR, more energy is required, which results in F/F and EGT increase, while there is no change in N1. The low-pressure turbine has a smaller work-per-blade ratio, therefore, is less responsive to in-flight monitoring. In general, expect the reverse patterns: N1 decreases, EGT and F/F increase, and N2 is insignificant.

Vibration Monitoring Engine malfunctions that indicate a change in vibration level fall into two general categories: (1) type of failure that produces an immediate unbalance, such as, a broken turbine blade, evidenced by a sudden change in vibration level. (2) type of failure indicated by a progressive change in the vibration level, such as bearing malfunctions, where an initial unbalance can progress into an eventual failure.

Instrumentation Error An individual instrument begins to give erroneous information. Trend in only one parameter is indicated. Note that a malfunction affecting the gas path of an engine will cause trends in at least two parameters.

CONCLUSIONS

A series of lectures designed to understand how aircraft engines work and fail has been successful in helping a group of researchers understand the issues in monitoring aircraft engines. Core lectures on engine components and failure modes, along with supplemental lectures and an airport visit, have been useful to people working on several projects, as evidenced by continued attendance and lively discussions.

REFERENCES

[1] AIA. Propulsion system malfunction plus inappropriate crew response (psm+icr). AIA/AECMA Project Report, November 1998.

[2] Philip G. Hill and Carl R. Peterson. *Mechanics and Thermodynamics of Propulsion*. Addison-Wesley, New York, NY, 1992.

[3] K. Huenecke. *Jet Engines: Fundamentals of Theory, Design, and Operation*. Airlife Publishing Ltd, England, 1997.

[4] David Lombardo. *Advanced Aircraft Systems*. TAB Books Practical Flying Series, Blue Ridge Summit, PA, 1993.

[5] Jack D. Mattingly, William H. Heiser, and Daniel H. Daley. *Aircraft Engine Design*. AIAA Education Series, New York, NY, 1987.

[6] John A. Reed and Abdollah A. Afjeh. A java simulator for teaching gas turbine operation. In *35th AIAA Aerospace Sciences Meeting*, Reno, NV, January 1997.

[7] I.E. Treager. *Aircraft Gas Turbine Engine Technology*. Glencoe Series, McGraw-Hill, Ohio, 1996.